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RECENT DEVELOPMENTS IN STRUCTURAL VERIFICATION OF SPACECRAFT

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Abstract

This paper gives a summary discussion of recent developments in the structural design, analysis, and test verification requirements applied to NASA spacecraft. Criteria for the selection of safety factors are addressed, along with the latest developments in Space Shuttle payload fracture cent rol requirements and implemental ion methodologies. The importance of early determination of the most cost-effective structural verification approach for a spacecraft and the influences of that approach on the design requirements and development program, along with test validation alternatives and rationale for selection, are also reviewed.

Introduction

Structures of spacecraft must be adequately designed to carry loads, provide physical support, and/or contain other hardware or substance. Verification of structural design by analysis and test is an integral and important part of the apace flight hardware development process. The primary objective of structural verification is to ensure that the flight system can survive the loads to be encountered in its service life, especially the quasi-static and vibro-acoustic loads imposed by the launch events.

During the conceptual design phase of a spacecraft functional requirements, including those for structural verification, are formulated. Structural verification requirements are commonly derived from two major sources; the launch vehicle operator (launch authority) and the organization responsible for the development of the spacecraft, Structural verification requirements set forth by the launch authority are primarily aimed at ensuring that the spacecraft to be launched (i.e., the pay load, asdefined by the launch authority) will have adequate structural integrity to withstand loads induced by the launch environment and will not be a threat to the safety of the launch vehicle and launch operations. These requirements are uniformly applied to all payloads to be launched or retrieved by a particular family of launch vehicles and are usually non-negotiable, On the other hand, structural verification requirements established by the developing organization are either institutional or project-specific, and are intended to minimize the probability of mission failure due to structural de ficiencies. These requirements are heavily influenced by institutional experience and tradition, and the level of mission risk that a particular project is willing to take. They are also considerably more flexible, and may be modified as hardware development progresses. It is not uncommon that some institutional requirements for structural verification are identical to those set forth by a launch authority, and that requirements in one group may envelop some in the other. To enable the selection of effective approaches to accomplish structural verification, an understanding of structural verification requirements and their basis and evolution is important.

Over the past three decades the structural design and configuration of spacecraft have gone through many changes. The large, highly flexible structural systems of modern spacecraft, such as the Hubble Space Telescope and Galileo, are subjected to structural ven fication requirements significant y different from those imposed on the structural design of the small and relatively rigid earth-orbiting satellites, such as Pioneer and Ranger, that were launched in the late 1950s and early 1960s. In the 1980s, the operation of the Space Shuttle added several new considerations, such as fracture control, for structural verification of payloads developed for manned space flights. It was also in the 1980s that the increasingly wider applications of advanced materials, notably the

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high-modulus graphite/epoxy composites, to primary load-carrying structures prompted the urgent need for verification criteria specifically established for nonmetallic and bonded structures, Finally, two important trends have developed during the last two decades: (1) several new families of expendable launch vehicles have been put into commercial service by domestic and foreign operators, and (2) more space missions are being developed by joint efforts of different countries. These trends have added new considerations to structural verification of payloads developed for multiple launchers or for missions with international partners.

In parallel to requirement changes, the approach and implementation methodology of structural verification have also continuously evolved over the years. In the 1950s and 1960s, it was typical to build one or more engineering model prototypes as the precursors of the flight unit, The prototypes were qualification-tested, usually under a set of very conservative test loads and environments, in order to seek out the weak links in the structural system. Based on the test results, remedial design actions could be identified and implemented, and test-qualification was repeated if deemed necessary. For a structural development program based on this prototype verification approach, the flight structure would not be qualification tested and was subjected only to less severe flight acceptance testing to verify the adequacy of workmanship. The prototype approach of structural verificat ion worked quite well for the spacecraft developed during that time period, for that they were mostly earth-orbiting satellites with relatively simple structural designs. The fabrication of prototypes and flight spares could be done quickly and at reasonable costs. As space flight structures became larger and more complex in the 1970s and 1980s, building prototypes for the purpose of test-qualifying structural designs also became either prohibitively expensive or not feasible for programmatic masons such as schedule and facility constraints. The protoflight approach of structural development, in which only one structural system is built and used for both test-qualification and actual flight, has become increasingly popular in recent yearn. Along with the widespread acceptance of the protoflight approach of structural development, the role of testing in verifying structural strength has gradually diminished. Marry structures that would have been qualified by a static-load test in the early days are now qualified by analysis alone, by equivalent dynamic tests, or component-level development tests along with analysis,

NASA is currently undertaking several development efforts aimed at improving cost-effectiveness of structural verification, Working groups have been chartered to develop standards on factors of safety, loads definition, environmental testing, material characterization and ground support equipment, The working groups on factors of safety and loads definition have produced white papers documenting fundamental understanding and agreements of the participating NASA centem in the respective technical areas. In the area of fracture control, a fresh look is being taken by NASA on the existing Space Shuttle payload fracture control requirements and the implementation methods that are currently being used to meet these requirements. The Air Force has also initiated a multi-year effort to develop enhanced technology for composite overwrapped pressure vessels and to update the existing design and verification criteria for metallic pressure vessels used in space flight systems.

This paper provides a summary discussion of recent developments in structural verification of spacecraft, as well as those related to pressure-vessels and fracture control of Space Shuttle payloads.

Considerations in Structural Verification

Verification of the structural design for a NASA mission often involves many conflicting technical and programmatic considerations. The ultimate goal of structural verification is to ensure that the flight system is structurally safe and flight worthy as evidenced by compliance with the requirements imposed by the NASA center responsible for that particular mission. Presently there are varying structural design and verification requirements and implementation approaches at the different NASA centers, This lack of uniformity of NASA structural verification requirements has caused difficulties for organizations that develop flight structures for different centers or for missions managed by multiple centers. In order to establish a set of minimum structural design and verification requirements that can be uniformly accepted by all centers, the NASA Working Group on Structural Factors of Safety and Test Verification was formed to prepare guidelines for the development of a NASA standard in this area. The major findings of this Working Group are included in the following discussions on several important issues that are often considered when selecting a cost-efficient structural verification approach[1]:

Manned vs. Unmanned Mission

Structural design requirements have been traditionally more stringent for systems developed for manned missions. For example, structures of payload systems that are to be launched or retrieved by the Space Shuttle are required to use higher factors, However, when certain programmatic factors are being taken into consideration (such as developing common structures for different missions, and retaining the flexibility of switching launch vehicles in the middle of the program), the advantage of using slightly lower factors of safety for unmanned hardware often becomes less important although such hardware may still be subjected to less stringent verification consistent with established mission risks and safety requirements. The Working Group recommended that the same minimum factors of safet y be applied to both manned and unmanned flight system,

prototype vs. Protoflight Approach

Qualification of the design of flight structures is normally accomplished by building a separate structural unit, i.e., a prototype that sometimes is called the qualification unit or model, and subject this prototype to static testing or some equivalent testing. With the increasingly severe cost and schedule constraints imposed on NASA flight projects, more and more of them have rejected the prototype qualification approach and adopted the protoflight qualification approach instead. The protoflight qualification, wherein no prototype is built and the flight unit is subjected to qualification-level testing, along with proper component-level developmental tests and thorough analytical verificat ion of strength, can usually provide adequate confidence that the structure is flight worthy. In order to preclude detrimental yielding of the flight structures during the protoflight testing, however, the design yield factor of safety must be higher than the qualification test factor, The Working Group recommended that protoflight qualificat ion be accepted for structures of spacecraft, payloads, and flight instruments.

Applicat ions of Test Methods

The Working Group categorized the commonly used structural test methods based on their usage. That is, structural tests are used to verify: (a) strength, (b) analysis models, and (c) workmanship.

Strength verification tests are normally static tests covering all significant load cases. The magnitude of the static test loads equal to the limit loads of the structure multiplied by the required test factor. In some cases, other tests, such as centrifuge and sine burst, if more effective in producing realistic qualification loads in the test structures, can be acceptable alternative-s to static tests.

The requirement to verify analysis models should normal] y be met by performing modal survey tests on the flight or flight-like structures. influence coefficient tests, in which load-vs.-displacements data are obtained, can also be used to verify structural analysis models. Test levels for both modal survey and influence coefficient tests are significantly lower than the limit loads, These tests should be properly instrumented to provide sufficient data for correlation with the analytical model. The tests should also be repeated at various levels to evaluate linearity and, for modal survey tests, to characterize structural damping.

Workmanship tests should be performed on the integrated flight systems and generally include sine and/or random vibration tests, acoustic tests, and pyro shock tests. Proof testing using statically applied loads are commonly required to verify workrnanship of bonded joints such as those in composite struts.

Test vs. No-Test Opt ion

NASA normally requires that the design of a flight structure be verified by both analysis and testing. Over the past two decades, however, structural verification by analysis only has become increasingly popular and is accepted by many NASA centers on a case-by-case basis. This structural verification approach is commonly known as the "no-test" or "analysis-only" option. The origin and development history have been previously studied[2]. Some of the factors that justify the increased reliance on analysis to qualify structural designs are: (1) advancements in computer-aided methods have made analyses and simulations more accurate, especially for structures that behave nonlinearly under operating loads and structures that are geometrically very complex and have complicated load paths; (2) many well-supported, general-purpose structural analysis codes, (e.g., NASTRAN and ANSYS) have become readily available and widely accepted; (3) increased cost of structural testing and the possibility of inadvertent damage has increased the pressures to eliminate the hardware safety risks associated with testing protoflight structures; (4) ground testing of a flexible space structure in its in-orbit configuration and under all critical conditions is difficult and in certain cases, even impossible; and (5) analysis usually costs less and can be done faster than testing.

The conditions under which structural verification without testing is acceptable are currently defined by individual NASA centers on a case-by-case basis. After considerable discussion and debate, the Working Group concluded that no standard criteria should be specified for general acceptance of the "no-test" option. However, the Group agreed that this option of structural verification may be used when supported by an acceptable engineering rationale. Some examples of acceptable rationale on which to base such an approach are:

1. The structural design is simple (e.g.; statically determinate) with easily-determined load paths, and has been thoroughly modeled and analyzed for all load conditions.

2. The structure is similar in design detail and overall configurate ion to a previous structure which was successful y test verified, with good correlation of test results to analytical predictions.

3. Development and/or component tests have been successful y completed on all critical elements of the structure which are difficult to analyze. Good model correlation to test results has been demonstrated.

The Working Group felt very strongly that increasing the design factors of safety does not by itsel f justify a "no-test" approach.

Deterministic vs. Probabilistic Method

Many of the parameters affecting the structural integrity of flight hardware have uncertainties, such as material property variability y, loads and environments variations, and analytical methods inaccuracies. Design factors of safety and test factors are intended to conservatively compensate for those uncertainties. Currently, all NASA centers use deterministic structural veri ficat ion criteria, and experience has shown these deterministic criteria to be adequate in most cases. An alternative approach which has received much attention is a probabilistic method, wherein knowledge (or assumptions) of the statistical variability of the various factors is used to select design criteria which achieve an overall confidence level.

Tbe Working Group determined that a standard approach to establish design and test criteria baaed on probabilistic methods is not practical at this time, but should be considered for future development. Recently, NASA has commissioned and completed a agency-wide survey on probabilistic structural analysis methodology and knowledge base, as a prelude to formulate a unified approach to incorporate probabilistic methods into existing NASA structural design and verification practices. The survey report[3)] describes in detail the current research, projects, software, methods, at various NASA centers, including 'the Probabilistic Failure Assessment (PFA) method[4&5)] developed at JPL for the past six years. The PFA method, employed to conduct risk sensitivity analyses for selected failure modes, is particularly useful in defining structural design and verification requirements when uncertainties exist about important governing parameters. JPL is currently planning to use the PFA method for structural design and verification of future small, low-cost missions, such as the Pluto Fast Fl yby mission, for which design conservatism and redundancy used in the past must be reduced or eliminated to meet more stringent mass and performance requirements.

Force-Limiting for Vibration Testing

Vibration testing, such as sine and random tests, is an important part of structural verification. In conventional vibration tests, the input vibratory motion is specified but the reaction force between the test item and the shaker is ignored. For typical space flight assemblies and equipment such as electronic boxes and science instruments, the mechanical impedance is comparable to that of the lightweight, flexible mounting structures so that the combined motions involve only modest interface forces. During a vibration test, the test item is hard-mounted to the shaker which, compared to the flight mounts, is much heavier and more rigid. Large reaction forces at the interface between the test item and the shaker develop as the test item goes into resonance. These reaction force-s often cause artificial test failures. Historically, this problem haa been addressed by developing "bullet-proof" (i.e., overly conservative) designs or incorporating a flight or flight-like mounting structure in the test.

Over the past four yeara, JPL has developed a vibration test method that more closely simulates a real-life flight environment. This test method implements force-limiting as an additional control of the teat inputs so that the vibration experienced by the test item is as it would be in flight, The specifications of force limits are derived on the basis of the interface impedance, which can be derived either from experimental data obtained by impacting hammer testing or by analysis. Several improved analysis methods for deriving force specifications are current] y under development[6&7]).

Force-limiting has been successfully applied to vibration testing of several JPL flight systems, including the Wide-Field/Planetary Camera (WF-/PC 1 I) for the Hubble Space Telescope. The use of this emerging technique is also under consider by other NASA centers.

Design Factors of Safety and Test Factors

The core product of the Working Group was a set of minimum design factors of safety (FOS) for verifying NASA space flight structures, These FOS requirements cover both the "prototype" and "protoflight" verification approaches. A significant point with regard to the recommendations is that the same minimum requirements apply to all flight systems whether they are for "manned" or "unmanned" missions. It was pointed out that distinctions in that regard might, however, be made in the degree of stringency applied in the verification program, The factors for various classes of flight structures are summarized below:

Metallic Structures

The minimum design and test factors for metallic structures, excluding threaded fasteners used in preloaded joints, were derived primarily based on the current Space Shuttle payload structural verification requirements[8]). These factors are listed in Table I.

Non-Metallic Structures

Non-metallic structures, excluding parts that exhibit brittle failure modes such as glass components, developed for NASA space flight missions are to be designed and verification tested to factors listed in Table 11, This class of structures include components made of composite lay-ups, metal matrix, metallic and non-metallic sandwich structures, and adhesive joints.

Fasteners Used in Preloaded Joints

When used in space flight systems, the preloaded fasteners usually form critical links in major load paths of the structure, the appropriate strength and gaping of bolted joints desert special attention. A method for the design and analysis of the preloaded joints in Shuttle payload systems has been developed). The minimum design and test factors for preloaded fasteners are listed in Table 111. In addition to strength analysis and testing, all preloaded joints shall be analyzed for gaping using a FOS of 1.2 for fail-safe joints and 1.4 for joints that are not fail-safe.

Glass and Brittle Components

The minimum design and test factors for pressurized and non-pressurized glass components are. specified in Table IV. Structural integrity of all pressurized glass components is to be verified by both analysis and testing except that some nonpressurized glass components meeting the "no-test" criteria may be verified by analysis only with a ultimate design factor of 5.0 minimum. Protoflight tests of glass components should be configured to simulate flight-like boundary conditions and loading and, for pressurized glass components, should be conducted in an inert environment. It is recommended that the unloading time for protoflight glass components be as short as possible in order to prevent undetectable flaw growth during the unloading phase.

Application of Minimum Factors

The design and test factors listed in Tables 1-through IV are the minimum required values for NASA space flight structures and should be applied equally to both mechanically and thermally induced loads (stresses) to determine margins of safety (M. S.) as follows:

$$M.S. = \frac{\text{Allowable Load or Stress}}{\text{FOS} \times (\text{Limit Load or Stress})} - 1.0$$

It should be emphasized that the factors of safety listed in Tables I through IV were developed in the context of structural and mechanical systems designs which are amenable to engineering analyses by current state-of-the-art methods and conforming to standard aerospace industry practices. More specifically, the designs must utilize materials whose mechanical properties are well characterized for the intended service environments, and to use configurations which are statically and dynamically stable under all design conditions. For reusable and multi-mission hardware, these factors of safety are applicable throughout the design service life and all of the missions, therefore design considerations must include material property degradation under the service environments, inspectabilit y for detection of darnage from unexpected causes, and instrumentation to ensure that design limits are not exceeded.

Application of the minimum factors of safety also assumes that the structures are made of well-characterized materials and the "A "-basis material allowable (including effects of environmental conditions), as designated in the latest version of

MIL-HDBK-5[10], or equivalent is used in calculating the margin of safety. It is further assumed that the service environments and design limit loads are well-defined and that acceptable manufacturing and process controls are used in the hardware fabrication and handling. Acceptance of the minimum test factors is also based on the use of test hardware typical of the flight configuration.

Factors of safety on yield are not specified for non-metallic structures, glass components, and fasteners. These structures and components should be designed to preclude any detrimental permanent deformation or functional degradation of the flight system under the design limit loads and, for programs employing the protoflight verification approach, the qualification test loads.

Currently, JPL is developing a NASA standard based on the above-discussed guidelines established by the Working Group. Upon completion of this NASA standard, current plans are to hold a government and industry workshop or conference to familiarize the engineering community with the underlying rationale and recommended practices in applying the standard.

Selection of Structural Verification Approach

The tight budget and schedule constraints which are imposed by commercial and government sponsors of flight spacecraft projects require selection of the most cost-effective structural verification methods, in some cases with requisite acceptance of some increase in risk. A rigorous approach to structural verification in such cases requires a clear definition by the sponsor and project management of the acceptable level of risk of failure during a verification test (causing increased cost and schedule delays) and during the actual mission (resulting in performance loss). The total mission cost of increased structural mass to permit higher design factors of safety in lieu of structural tests must be known in order to judge the cost-effectiveness of this trade.

Among the structural verification methods which can be considered are various types and combinations of analyses and tests. Dynamic design loads can be conservatively approximated for simple systems based on historical precedent (such as the mass acceleration curve approach developed in the 1980s at JPL[11]) and later verified in a system level vibration test. Structural strength may be verified by static application of various bounding load combinations, at the component, sub-assembly or system level, or by dynamic tests such as vibration or acoustics tests at various levels of assembly.

The degree of test verification to be used in combination with detailed structural analysis should depend largely on the complexity and experience base with the structural design. Structural configurations for which previous experience has shown test results to correlate well with analysis can with high confidence be verified by tests limited to a few of the most critical components and load conditions. Conversely, where past experience has shown certain types of structure to be difficult to analyze reliably, emphasis should be on early more comprehensive testing with reduced analysis detail and effort,

A significant development cost and schedule saving can in some cases be realized by designing to high structural factors of safety in order to reduce or eliminate verification tests. As stated earlier, the cost effectiveness of this approach requires some knowledge (or assumptions) concerning the effects of increased mass on mission cost. Once it has been determined to be a cost-effective trade, it may be permissible to verify structural integrity by analysis alone, provided that an acceptable engineering rationale is developed. It should be emphasized that increasing the design FOS alone, with the support of logical engineering rationale, does not by itself justify a "no-test" approach,

The protoflight verification test approach, in which the actual flight structure is tested, can be very cost and schedule effective if properly designed and implemented. The flight structure must be made available at appropriate times during the spacecraft fabrication and assembly in a configuration such that it can be instrumental, loading devices attached at critical locations, and installed in a test fixture or chamber. Secondary structures or adaptera which cannot be made available for this must be tested separately. A major constraint on protoflight tests, whether they be static load or dynamic tests, is that care must be taken to ensure that no unnecessary detrimental yielding will occur which could impair flight performance. This will normally require an increased design factor on material yield strength plus careful post-test inspection to verify critical alignments.

Fracture Control Requirements and Implementation

The concept of fracture control was originated from the long-recognized fact that regardless of the care taken in material production and component fabrication, small cracks or crock-like flaws may be present in load-carrying structures. Under cyclic loadings of magnitudes over certain levels, these cracks or flaws will grow and, if propagated to critical sizes, the growth may become unstable and cause the structure to fail in a catastrophic manner. Over the years, fracture control methodologies were developed to reduce the possibility of catastrophic failure due to propagation of pre-existing cracks in structures. These ranged from improved material processing and manufacturing procedures for parts of higher fracture resistance to special loading spectrums devised to effect retardation of crack growth.

Prior to the 1970s, the application of fracture control requirements was limited mainly to pressurized structures such as aircraft fuselages and pressure vessels, including those used in space flight systems, This was because a pressure vessel usually contains a large amount of energy and its fracture will most likely cause catastrophic event and impact safety of personnel and facilities, The applications of fracture control were greatly expanded in the early 1980s when the Space Shuttle was put into operation. Fracture mechanics was one of the structural design considerations of the Shuttle and NASA also imposed fracture control on all payloads to be flown and retrieved by the Shuttle. In 1985, the NASA Fracture Control Methodology Development Panel consisting of representatives from all NASA field centers, the Air Force, and the European Space Agency (ESA) was established, The primary function of this panel is to provide a forum to discuss and resolve issues related to the implementation fracture control. Among the many accomplishments of this Panel, two are especially significant: (1) the establishment of a set of uniform Shuttle payload fracture control requirements, specified in NHB 8071 .-112), that have been accepted by all NASA centers. Similar fracture control requirements were adopted by ESA[13)]; and (2) the development of NASA/-FLAGRO, a crack-growth analysis computer program[14)]. This program, currently being maintained by NASA Johnson Space Center, contains a comprehensive library of crack models, an extensive database of fracture properties of space structural materials, test-verified Space Shuttle launch and landing load spectrums, and initial crack sizes screened by standard nondestructive examination (NDE) methods. Over the past few years, NASA/-FLAGRO has become the industry standard for safe-life assessment of fracture-critical parts.

After more than a decade of practicing fracture control on Shuttle payloads, many practitioners at NASA and in the industry have realized that fracture control should and can be made more cost-effective. Several efforts have been taken by NASA Fracture Control Methodology Panel to achieve this aim. These include:

Johnson Space Center (JSC) is leading an agency-wide effort to update NHB 8071.1. ‘f’he main objective is to simplify the identification and acceptance requirements of fracture-critical parts.

JPL is summarizing lessons learned and developing guidelines for cost-effective implementation of fracture control, A NASA fracture control guidelines document is scheduled to be published in 1995,

JPL is conducting a comparative assessment of existing methods used to analyze containment. Included in this survey is the containment design method developed by ESA in 199115). Results of this JPL effort will be incorporated in the above-mentioned guidelines document.

NASA's Marshall Space Flight Center (MSFC) is studying the feasibility of applying a "cut-off" at 65-70 % of to the average K_{Ic} value used for safe-life analysis. If incorporated, this will make NASA and ESA requirements for fracture properties consistent with each other.

. JPL is developing a methodology to establish the acceptabil it y of parts with NDE-detected cracks or crack-like flaws.

JPL is proposing that a list of non-structural parts that are obviously non-fracture-critical and can be exempt from fracture control. Currently, the proposed list of "exempt" parts consists of thermal blankets, rubber seals, and harness.

JSC is developing a set of acceptance criteria for "low-risk" parts[16)]. A part that is fracture-critical is low-risk if it can be shown that the part has a very low probability of fracture failure. Low-risk parts, once identified, are re-classified as non-fracture-critical.

The revised fracture control classification logic, with the additional of the "exempted" and the "low-risk" parts categories, is shown in Figure 1. It is hoped that the above-mentioned revisions of NHB 8071.1 requirements can reduce the number of fracture-critical parts in Shuttle payload systems. Since the NDE inspections, safe-life analysis/testing, trainability, and documentation of fracture-critical parts are the major efforta of a typical payload fracture control program, reducing the number of parts that are labeled fracture-critical should yield significant cost savings,

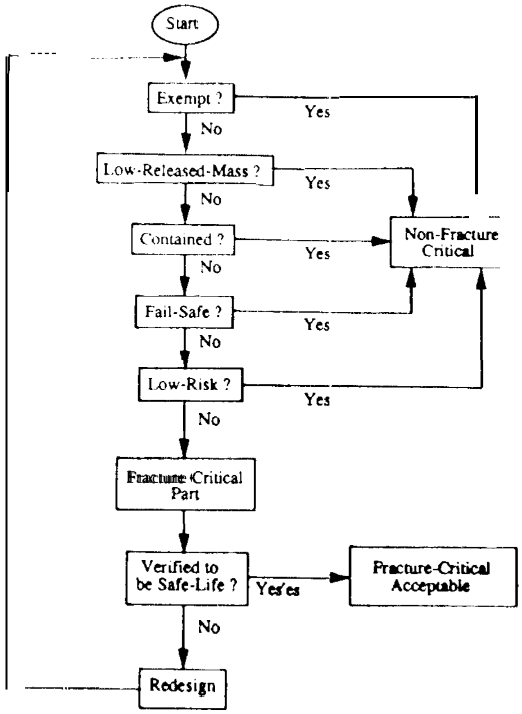

Figure 1. Revised Fracture Control Classification Logic

In addition to activities related to Shuttle payload fracture control, an agency-wide effort led by MSFC is also being undertaken to establish a set of top-level requirements. These requirements will be used to govern fracture control efforts of all on-going and future manned missions (including Space Station) and to extend fracture control as an optional quality control tool" for unmanned missions.

Design and Verification of Pressure Vessels

Because it is critical to mission and personnel safety, the design and verification of any pressure vessel used in a space flight system requires special attention. The Air Force developed and published a set of requirements for the design and verification of pressurized space and missile systems in the 1970s. These requirements, revised in 1984 and specified in the Air Force document MIL-STD-1522A[17], have been widely used by the industry. There are several drawbacks of MIL-STD-1522A when applied to NASA space flight programs, The major one is that NASA pressure vessels, unlike those used by the USAF, are not mass produced and in most case only one or two units of the same design are needed and fabricated. These one-of-a-kind vessels can not afford the luxury of performing destructive verification tests such as pressure-cycle and burst tests required by MIL-STD-1522A. Currently, NASA pressure vessels are designed and verified to a set of modified MIL-STD-1522A requirements, as specified in NHB 8071.1 and NHB 1700.7 B[18]. The important modifications include:

- NASA allows a proof test at a minimum of 1.5 times the maximum design pressure (MDP) and fatigue analysis showing a minimum of ten design lifetimes to qualify one-of-a-kind vessels. MIL-STD-1522A requires a pressure cycle test and a burst test for the qualification of all pressure vessel designs.

NASA requires, for analytical demonstration of vessels of a leak-before-burst design, crack growth analyses and disallow the use of the "ductile screening criteria" specified in an Appendix of MIL-STD-1522A.

NASA requires an additional NDE inspection of the welds in metallic pressure vessels after proof testing.

Recognizing that the MIL-STD-1522A document was released more than ten years ago and is now unable to meet the changing needs of its users (such as NASA), the Air Force initiated in 1992 an effort to update this document. In addition to addressing issues that were surfaced in the past decade, this effort also intends to reflect recent progress in pressure vessel technology, such as the use of aluminum-lithium and metal matrix materials. Requirements for range safety and the design and verification of ground support equipment (GSE) pressure vessels will be new additions to the updated MIL-1522A document,

One of the outstanding issues concerns the composite overwrapped pressure vessels (COPVs). The use of COPVs as pressurant tanks in space flight systems has become increasingly common, but their applications have often been impaired by the lack of safety requirements that can be met by existing technology. The lack of rational requirements is particularly apparent for the demonstration of damage tolerance of the overwrap. To resolve this, a study program is being performed by the Air Force, with NASA participation, to develop enhanced technology for COPVs. The objectives of this COPV technology program are stated in its workplan[19]: (1) to identify and evaluate, by both analytical and experimental methods, the critical design and manufacturing parameters; and (2) to formulate safety and quality assurance requirements, including those for the demonstration of damage tolerance, for the incorporation into the revised MIL-STD-1522A. Currently, the COPVs of interest are primarily graphite-epoxy composite pressure vessels with metal liners, up to 40 inches in diameter and with a maximum expected operat - ing pressure (M EOP) of greater than 4,000 psi.

Concluding Remarks

In response to the changing funding and mission environment NASA has initiated intensive requirement and technology development activities in the areas of structural verification and fracture control. The common goal of these activities is to improve the cost-effectiveness of structural verification and fracture control for future NASA missions. This will be accomplished by clarifying and simplifying the existing requirements, developing enhanced technologies that address outstanding compliant.e issues, and resolving differences in acceptance criteria and implementation approach. It is also hoped that some level of uniformity in structural verification and fracture control requirements can eventually be achieved - not only among a]] NASA centers, but also among NASA and its international partners such as ESA and NASDA.

NASA currently participates in the on-going Air Force endeavor to update the design and verification requirements for pressure. vessels, including the development of enhanced COPV technologies. Contributions have also been made by NASA in the area of improving the effectiveness of structural testing.

Results of the recent and on-going **efforts discussed in** this **paper will significantly impact structural** design and verification of all future NASA space missions. It is important to follow their progress.

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Table I Minimum Factors for Metallic Structures

Verification Approach	Ultimate Design FOS	Yield Design FOS	Qualification Test Factor	Acceptance/Proof Test Factor
Prototype	1.4	1.0	1.4	1.0
Protoflight	1.4	1.25	1.25	1.0

Table II Minimum Factors for Non-metallic Structures

Verification Approach	Geometry of structure	ultimata Design FOS	Qudifi- Test Factor	“ m
Prototype	Discontinuities	2.0*	1.4	1.05
	Uniform Material	1.4	1.4	1.0s
Protoflight	Discontinuities	2.0	1.25	1.0
	Uniform Material	1.4	1.25	1.0

* Factor applied to concentrated stresses

Table III Minimum Factors for Preloaded Fasteners

Verification Approach	Ultimate Design FOS	Qualification Test Factor	Acceptance/Proof Test Factor
Prototype	1.4	1.4	1.0
Protoflight	1.4	1.23	1.0

Table IV Minimum Factors for Glass and Brittle Components

Verification Approach	Loading Condition	Ultimate Design FOS	Qualification Test Factor	Acceptance/Proof Test Factor
Prototype	Nonpressurized	2.0	1.4	1.2
	Pressurized	2.0	1.4	1.2
Protoflight	Nonpressurized	3.0	1.2	1.2
	Pressurized	3.0	2.0	2.0